Phase Goldstone Bosons in the $^3P_2$ Phase of Neutron Matter and Neutrino Emmission

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At the high densities present in the interior of neutron stars, the neutrons are condensed into the superfluid phase. While this condensation has little impact on the equation of state, it can have an important role in determining the low-temperature energy-momentum transport properties. The spontaneous breaking of baryon number by the condensate gives rise to the familiar Goldstone boson, but in addition, the spontaneous breaking of rotational invariance by the condensate gives rise to three Goldstone bosons, one for each broken generator of rotations. These Goldstone bosons, which couple to the Z^0, provide a new mechanism for neutrino emission. Using a low-energy effective field theory to describe the dynamics of these Goldstone bosons we estimate the neutrino emissivity of dense neutron matter and show that their annihilation is the dominant energy-loss mechanism over a range of temperatures.

At relatively low densities we have a good description of nuclear interactions which are dominated by the attractive S-waves, with higher partial waves suppressed by powers of the typical momentum. As the density is increased the repulsive nature of the S-waves at higher momenta becomes important and at ~ 1.5 times nuclear matter density, the $^3P_2$ average interactions are the most attractive suggesting the formation of a $^3P_2$ neutron condensate. This has been known for sometime, and considerable work has gone into determining the magnitude of the $^3P_2$ gap as a function of density with the most sophisticated nuclear potentials and also with effective low-energy potentials.

In this work we point out that since a $^3P_2$ condensate spontaneously breaks rotational invariance, there will be three Goldstone bosons (angulons). In addition, baryon number is also broken, as in any superfluid, leading to the existence of another, well known, Goldstone boson. These modes will dominate the low-energy, low-temperature properties of the system. In particular they provide an important new mechanism for neutrino emission that is not exponentially suppressed at temperatures below the critical temperature, Tc.

We can make a rough estimate of the size of the contribution coming from angulon annihilation into a neutrino pair using dimensional analysis: $E \sim G_F^2\ T^9$. This estimate assumes that powers of the dimensionful quantities like the Fermi momentum k_F or the value of the gap Δ are not relevant. We will argue that this is indeed justified. The temperature dependence does not have the characteristic exponential suppression $\exp(-2\Delta/T)$ found in processes involving gapped fermions but it is one power of T higher than the electron-electron scattering contribution. By the other hand it is not suppressed by the low electron density present in b-equilibrated matter. There are two caveats with our estimate First it is not immediately obvious which, if any, is the coupling of two angulons to the neutral currents. Second, the annihilation process is proportional to two powers of the angulon density n(T).

Since the Bose distribution function depends on the energy E= v p of the angulon, we have $n(T) \sim T^3/v^3$. If the angulon speed v is small, the number of angulons is greatly enhanced, and so is the emissivity. For this reason it is important to get a handle on both the numerical value of v and the dependence of the emissivity with v. We estimated these factors using an effective theory to organize our arguments. A true model independent calculation is, unfortunately, not possible at the moment. A better assessment of the impact of angulon annihilation in the cooling of neutron stars requires the rates computed in this paper be inserted into a realistic cooling code.

REFERENCES

[1] P. F. Bedaque, G. Rupak and M. J. Savage, *Phys.Rev.C* 68:065802 (2003).